Modeling Studies of Optical Properties of Sprite Streamers and Their Chemical Effects on the Upper Atmosphere

Ningyu Liu

Department of Physics and Space Sciences
Florida Institute of Technology
Melbourne, FL 32901

Advisor: Victor P. Pasko

Department of Electrical Engineering
The Pennsylvania State University
University Park, PA 16802

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- Introduction to Sprites and Sprite Streamers
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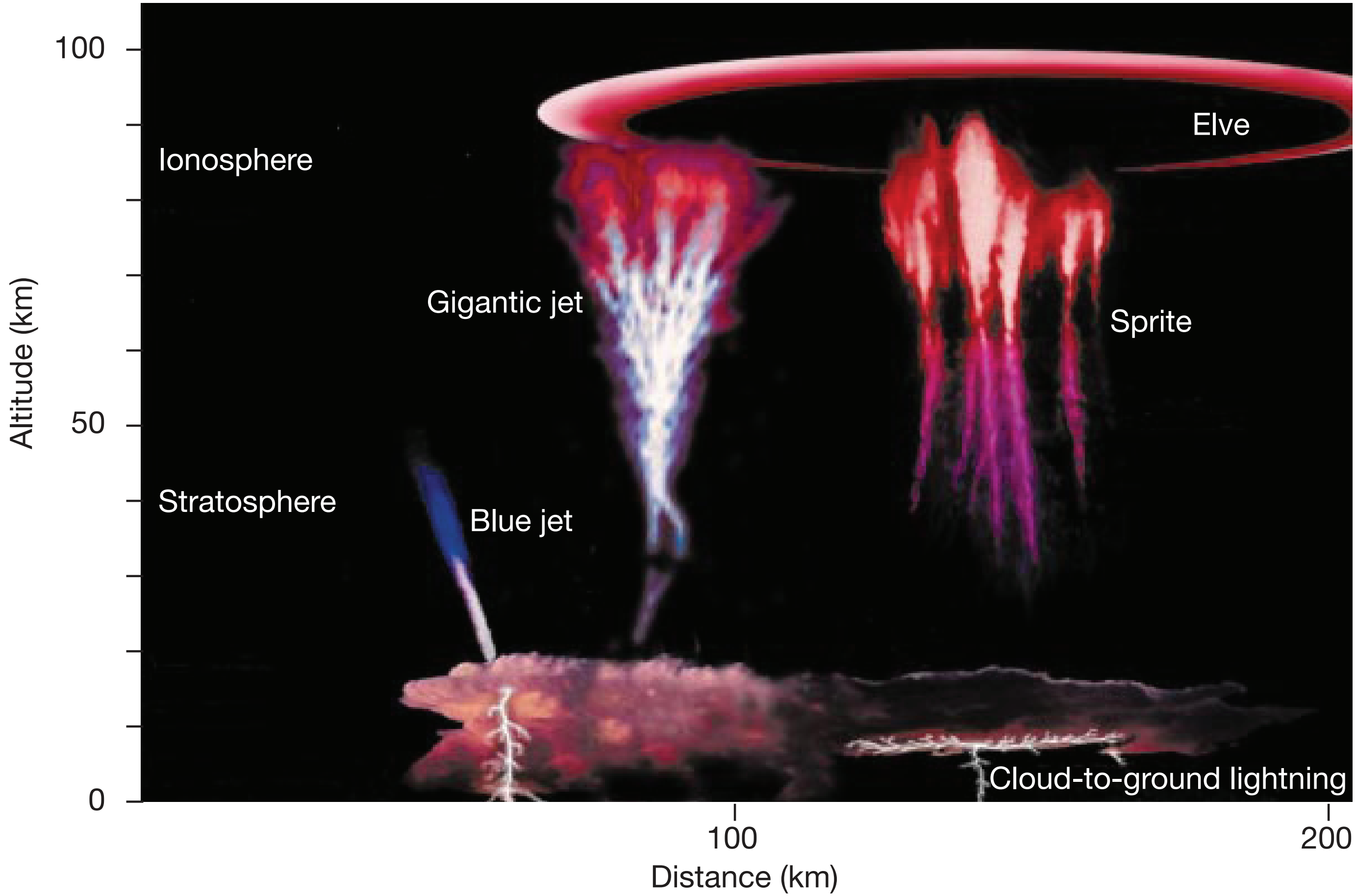
- Conclusions

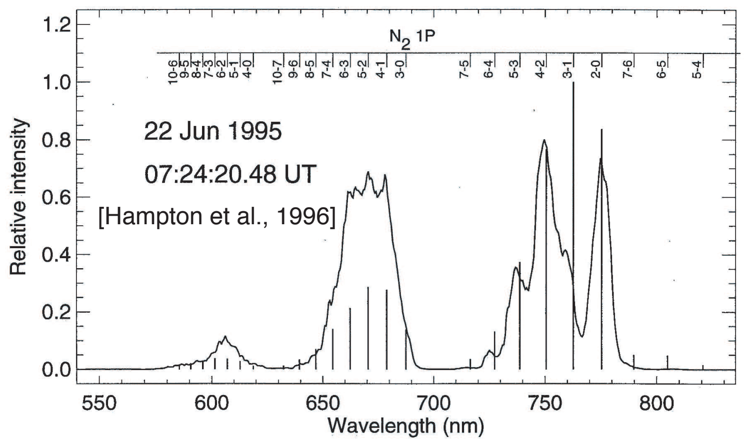
Transient Luminous Events



- Lightning-related transient luminous events [*Lyons et al.*, 2003; *Pasko*, 2003].

Sprite Spectrum

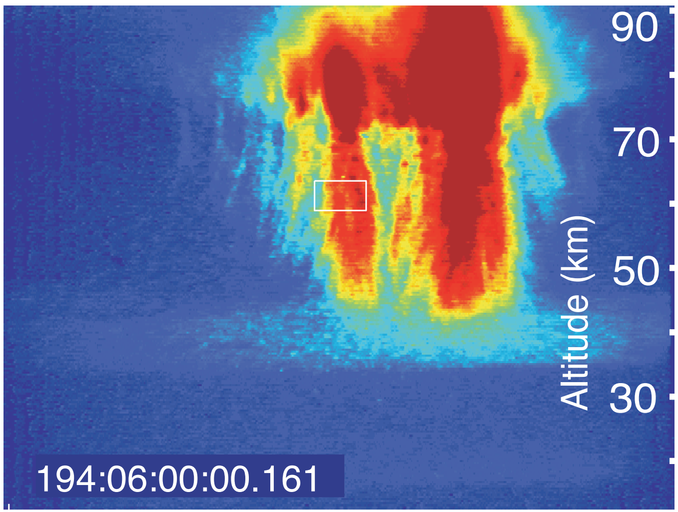
- A typical sprite spectrum is in the red region of the visible light [*Hampton et al.*, 1996]:

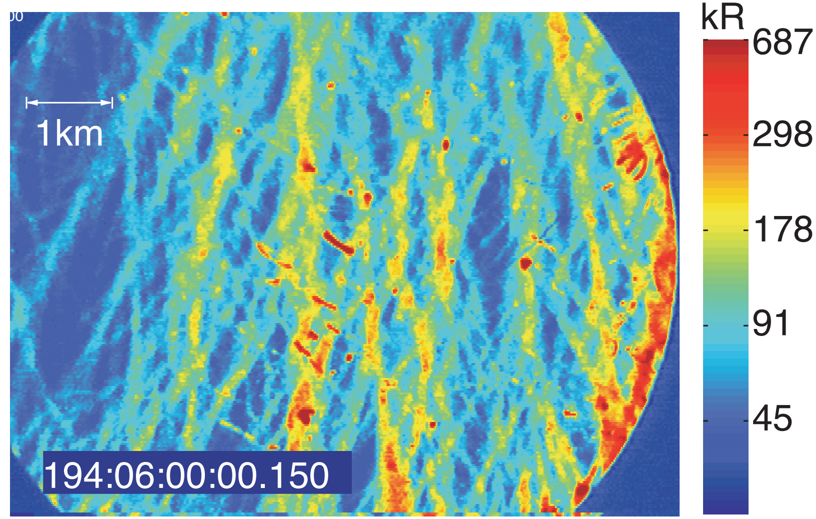


- Four major emission band systems of sprites [e.g., *Mende et al.*, 1995; *Hampton et al.*, 1996; *Armstrong et al.*, 1998, 2000; *Morrill et al.*, 1998, 2002; *Suszcynsky et al.*, 1998]:

Emission Band System	Transition	Excitation Energy Threshold (eV)	Lifetime at 70 km Alt.	Quenching Alt. (km)
1PN_2	$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+)$	∼7.35	5.4 μs	∼53
2PN_2	$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$	∼11	50 ns	∼30
LBH N_2	$N_2(a^1\Pi_g) \rightarrow N_2(X^1\Sigma_g^+)$	∼8.55	14 μs	∼77
1NN_2^+	$N_2^+(B^2\Sigma_u^+) \rightarrow N_2^+(X^2\Sigma_g^+)$	∼18.8	69 ns	∼48

Streamer Structure of Sprites

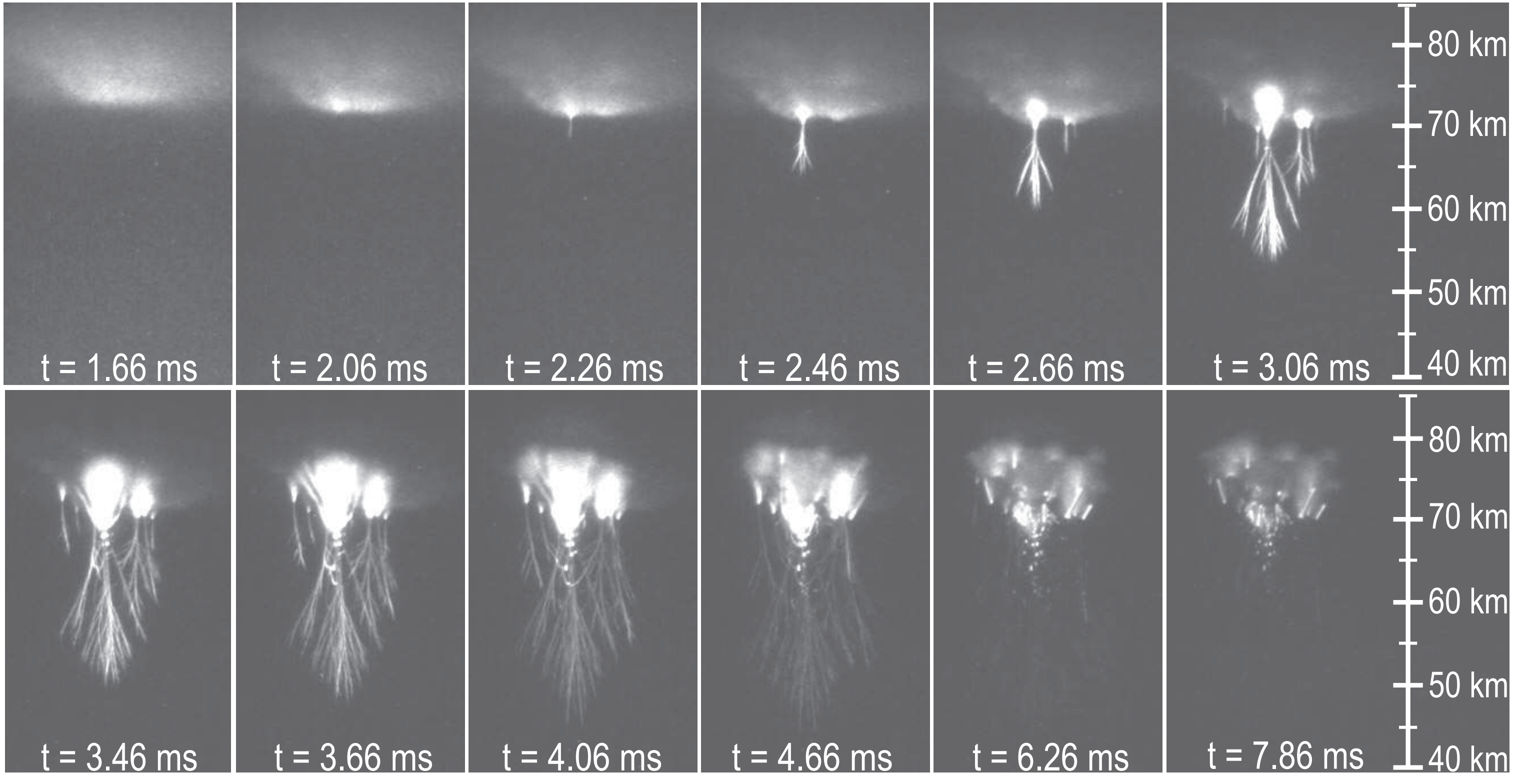




- Telescopic imaging of sprites. Wide (left panel) and narrow (right panel) field of view images of a bright sprite event [*Gerken et al.*, 2000; *Gerken and Inan*, 2002, 2003].
- The transverse scales of the streamer structures observed by *Gerken et al.* [2000] and *Gerken and Inan* [2002, 2003] range from 50 to 200 m.

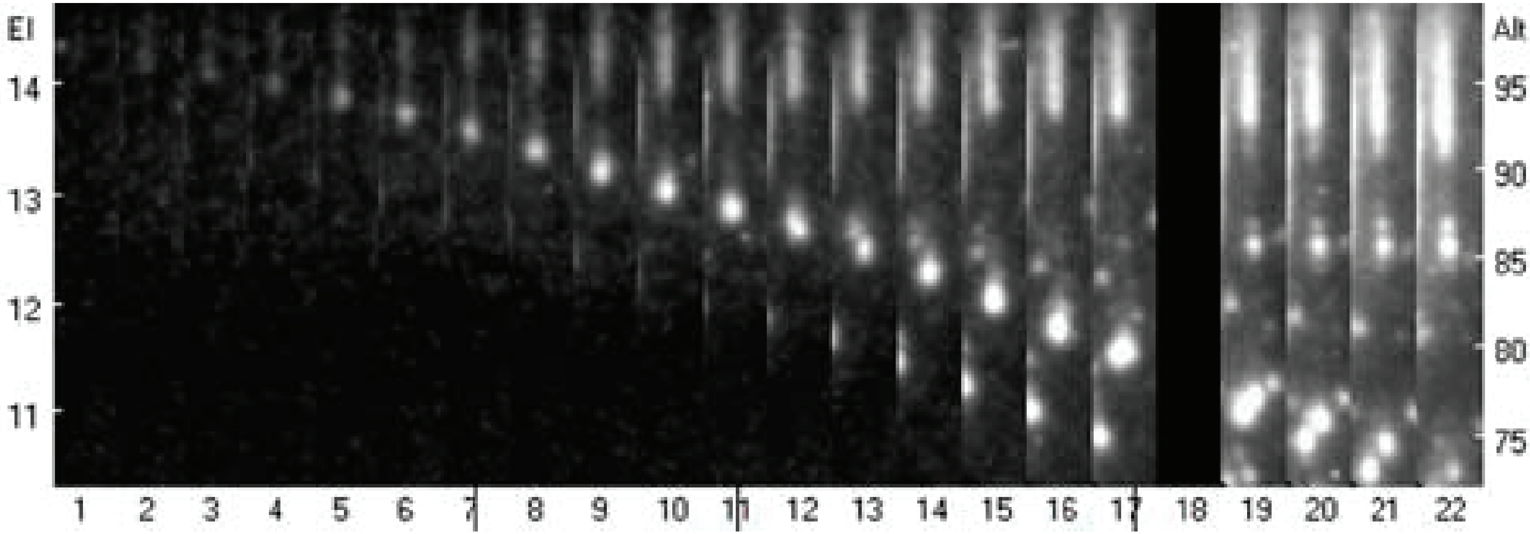
Recent Submillisecond Imaging of Sprite Development and Structure

- High speed sprite images (∼0.2 ms) obtained on August 13, 2005 [*Cummer et al.*, 2006].



Recent Submillisecond Imaging of Sprite Development and Structure

- Sprite images recorded at 10,000 fps [*Stenbaek-Nielsen et al.*, 2007].



- Emissions from sprite streamers are confined to the streamer tip [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007].
- The high-speed video records also show that sprite streamers accelerate and expand [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007].

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Streamer Model Equations

- The dynamics of a streamer are described by the electron and ion drift-diffusion equations coupled with Poisson's equation in a cylindrical coordinate system [*Liu and Pasko*, 2004]:

$$\begin{aligned}
\frac{\partial n_e}{\partial t} + \nabla \cdot n_e \vec{v}_e - D_e \nabla^2 n_e &= (\nu_i - \nu_{a2} - \nu_{a3}) n_e - \beta_{ep} n_e n_p + S_{ph} \\
\frac{\partial n_p}{\partial t} &= \nu_i n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p + S_{ph} \\
\frac{\partial n_n}{\partial t} &= (\nu_{a2} + \nu_{a3}) n_e - \beta_{np} n_n n_p \\
\nabla^2 \phi &= -\frac{e}{\epsilon_0}(n_p - n_e - n_n)
\end{aligned}$$

- The coefficients of the model are assumed to be functions of the local electric field and obtained from solutions of the Boltzmann equation [*Moss et al.*, 2006].

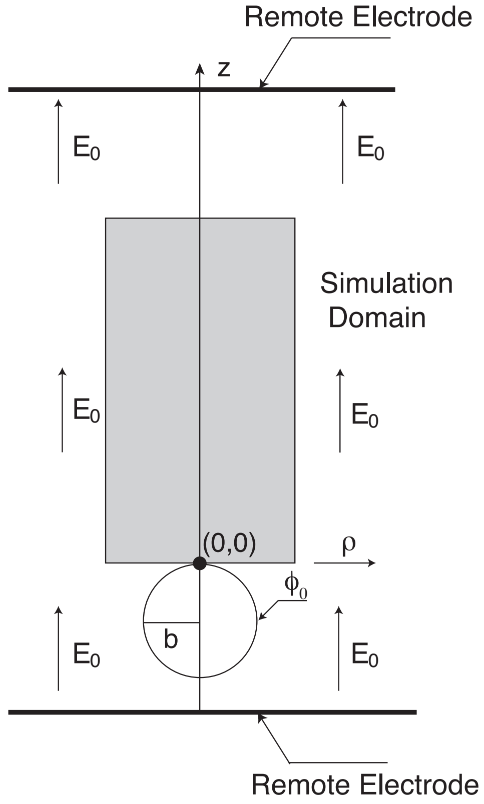
Optical Emission Model

- The number densities (n_k) of excited species is governed by the relation [*Sipler and Biondi*, 1972]:

$$\frac{\partial n_k}{\partial t} = -\frac{n_k}{\tau_k} + \sum_m n_m A_m + \nu_k n_e$$

where $\tau_k = [A_k + \alpha_1 N_{\mathrm{N}_2} + \alpha_2 N_{\mathrm{O}_2}]^{-1}$ is the total lifetime of state k, A_k is the radiation transition rate, α_1 and α_2 are the quenching rates due to collisions with N_2 and O_2 molecules, respectively, the sum over the terms $n_m A_m$ represents increases in n_k resulting from cascading from higher-energy states, and ν_k and n_e are excitation coefficient and electron density, respectively.

Simulation Domain



[*Babaeva and Naidis*, 1997]

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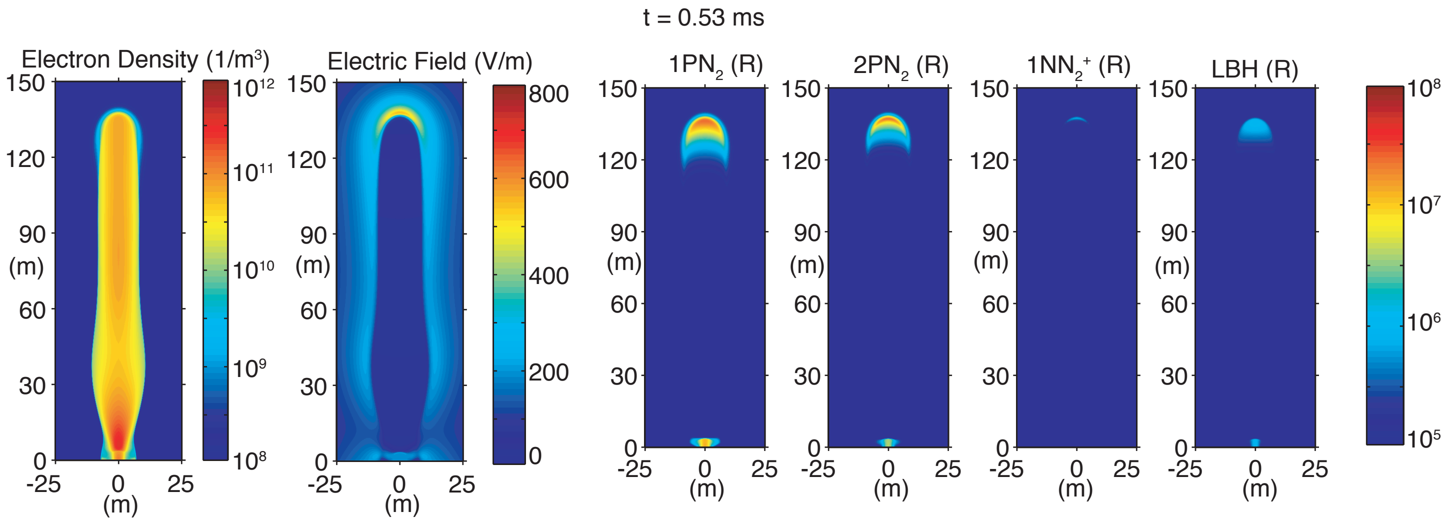
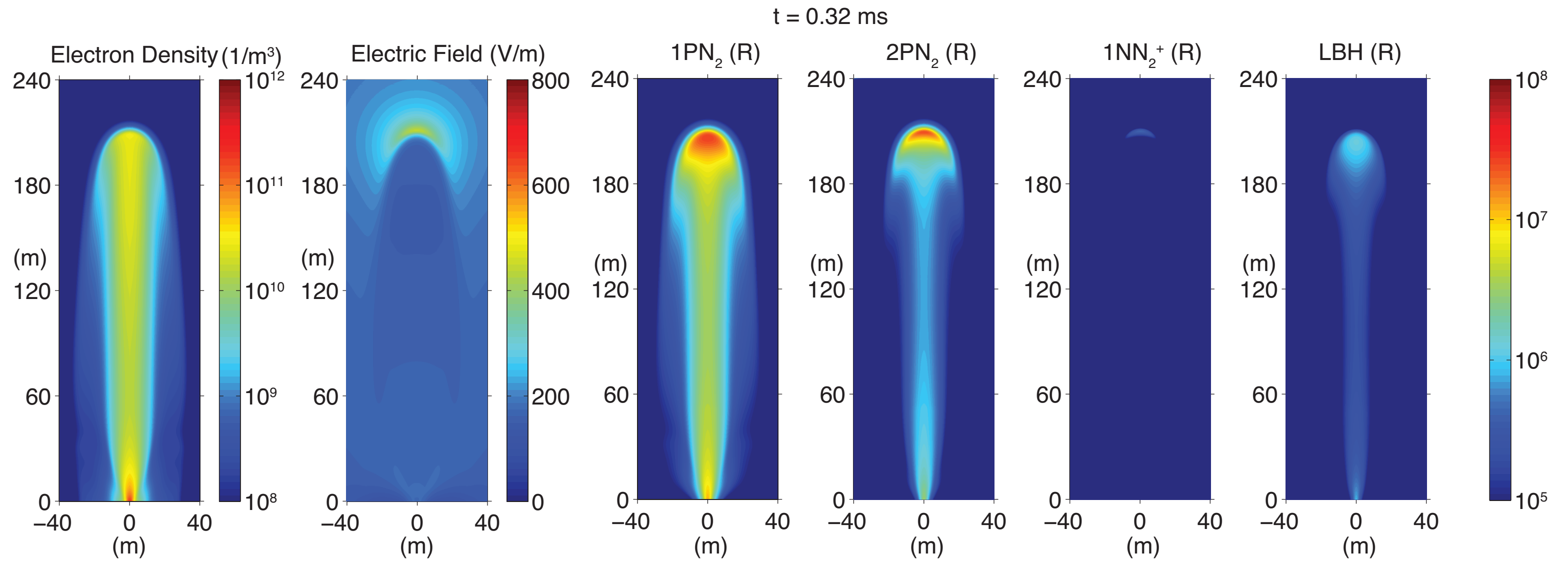
Modeling Results for a Positive Streamer at 70 km Altitude

- Modeling results for a sprite streamer developing in an ambient field $E_0 = 5 \times N_{70}/N_0$ kV/cm, where N_{70} and N_0 are air densities at 70 km and 0 km altitude, respectively.

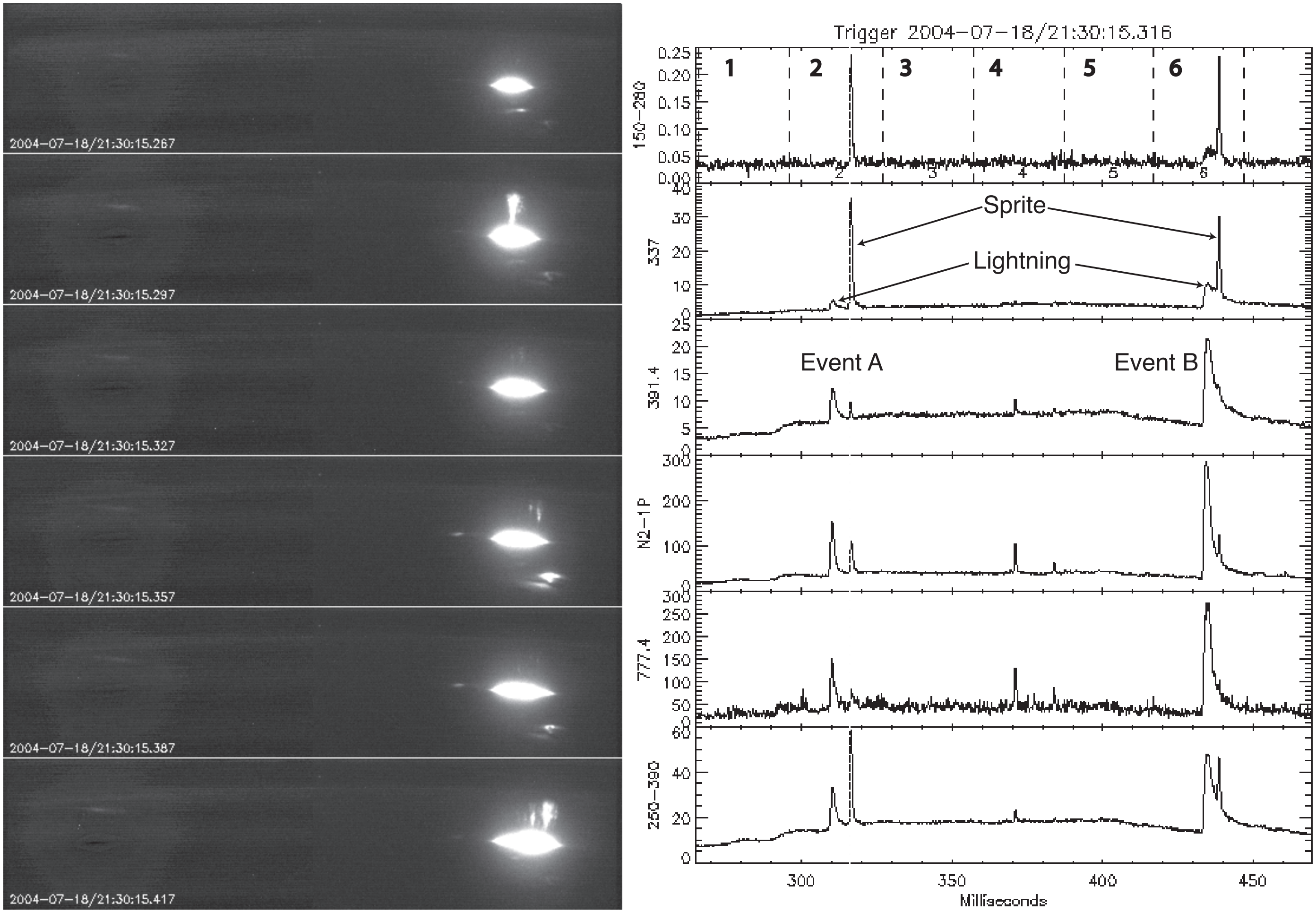


Modeling Results for a Negative Streamer at 70 km Altitude

- Modeling results for a sprite streamer developing in an ambient field $E_0 = 25\times N_{70}/N_0$ kV/cm, where N_{70} and N_0 are air densities at 70 km and 0 km altitude, respectively.



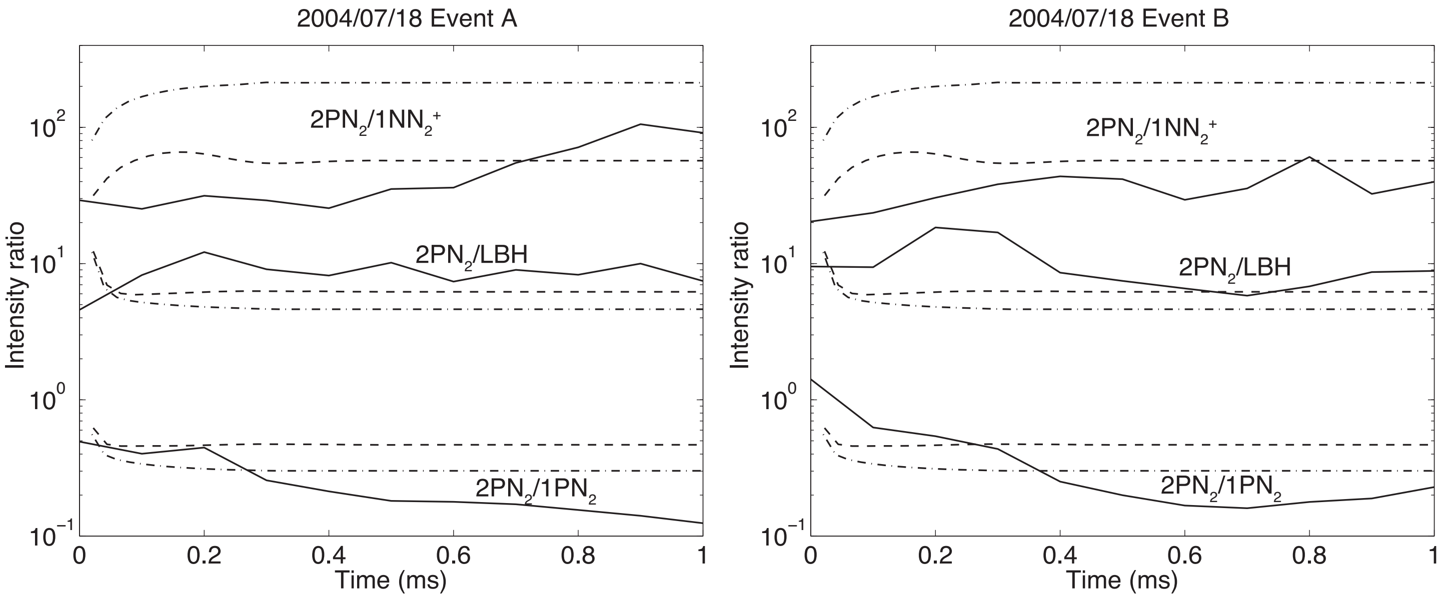
Sprites Recorded by ISUAL on FORMOSAT-2 Satellite on July 18, 2004



[*Mende et al.*, 2006]

Comparison of ISUAL Observations with Streamer Modeling

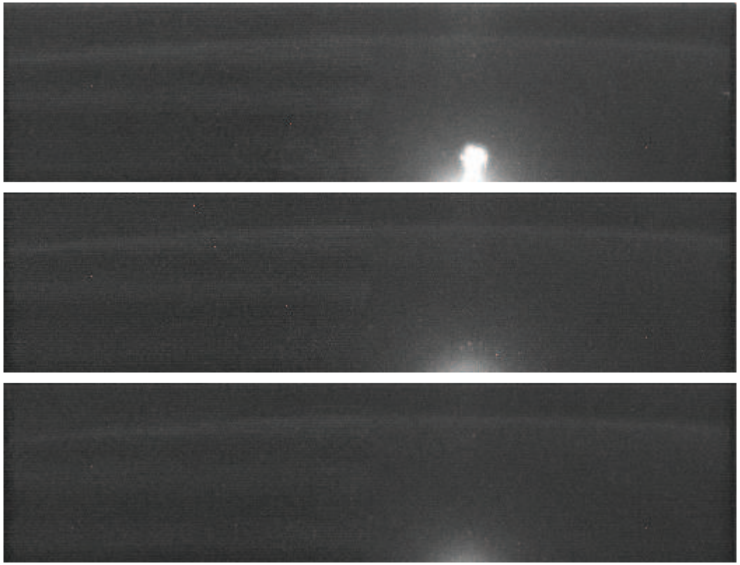
- We choose intensity ratios of $2PN_2$ to $1PN_2$, LBH N_2, and $1NN_2^+$ as our comparison quantities.

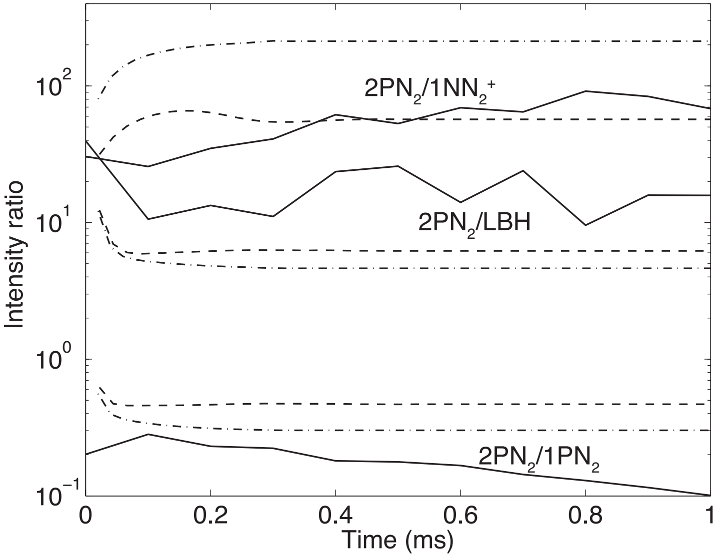


- Solid line – ISUAL observations; Dashed line – Modeling results for a positive streamer; Dashdot line – Modeling results for a negative streamer.

Comparison of ISUAL Observations with Streamer Modeling

Sprite event triggered at 2005/03/06 23:22:30.623

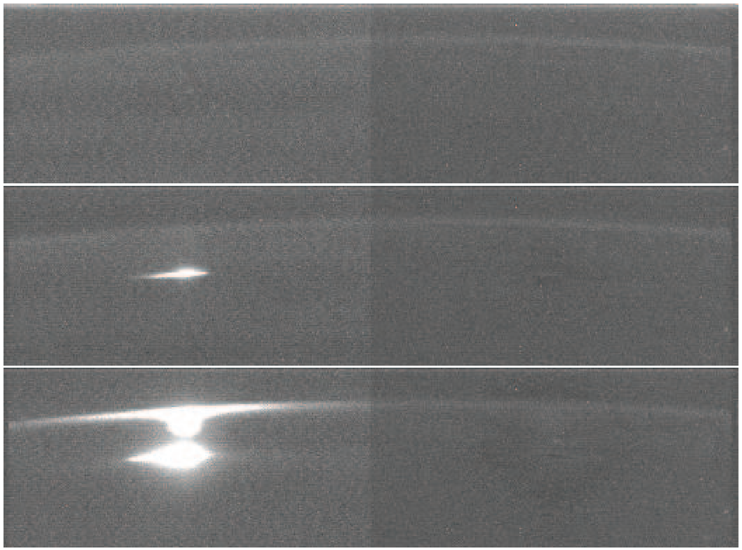


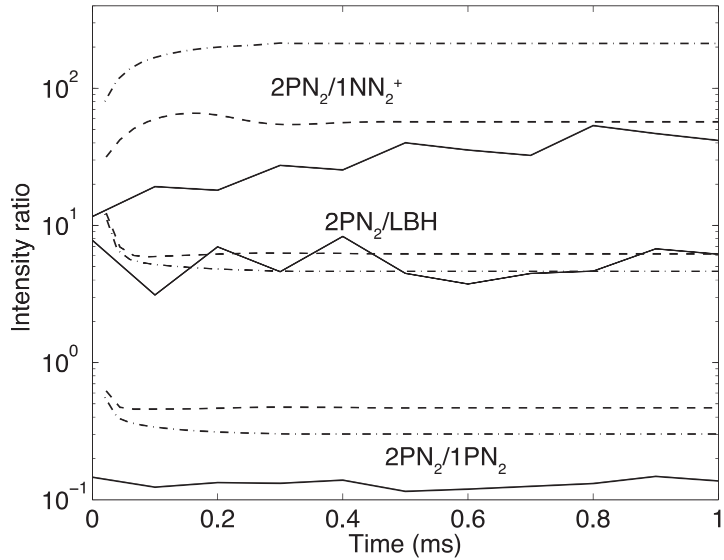


- Solid line – ISUAL observations; Dashed line – Modeling results for a positive streamer; Dashdot line – Modeling results for a negative streamer.

Comparison of ISUAL Observations with Streamer Modeling

Sprite event triggered at 2006/07/01 16:43:46.401





- Solid line – ISUAL observations; Dashed line – Modeling results for a positive streamer; Dashdot line – Modeling results for a negative streamer.

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Heating Model

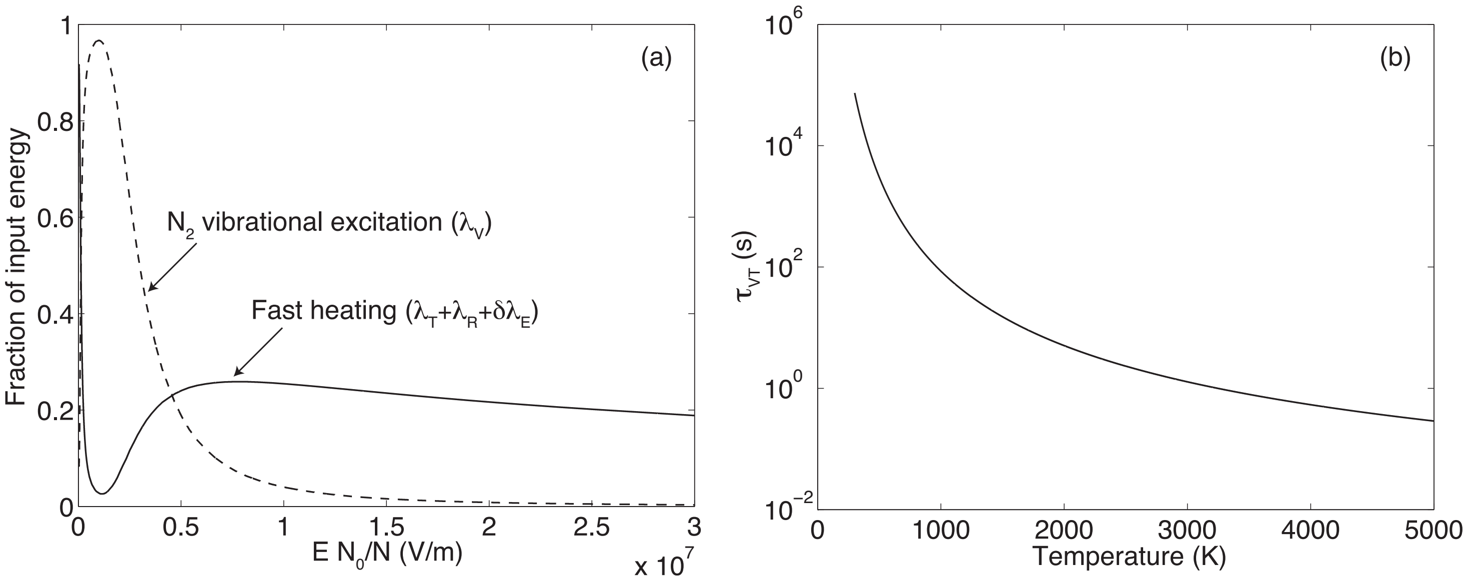
- The heating effects of a sprite streamer are taken into account using the model proposed in [*Aleksandrov et al.*, 1998; *Naidis*, 1999]:

$$\begin{aligned}
n_{\mathrm{N}_2}\frac{\partial \varepsilon_V}{\partial t} &= \frac{\lambda_V}{e} jE - \frac{\varepsilon_V - \varepsilon_V(T_g)}{\tau_{\mathrm{VT}}(T_g)} n, \\
C_V n \frac{\partial T_g}{\partial t} &= (\lambda_T + \lambda_R + \delta\lambda_E) jE + e\frac{\varepsilon_V - \varepsilon_V(T_g)}{\tau_{\mathrm{VT}}(T_g)} n
\end{aligned}$$

  where ε_V and T_g are the mean vibrational energy of N_2 molecules and gas temperature, respectively; λ_V is the fraction of input energy transferred to vibrational excitation of N_2 molecules; λ_T, λ_R, and λ_E are the fractions of input energy transferred into translational, rotational, and electronic degrees of freedom of neutrals, respectively; $\delta = 0.3$; $\varepsilon_V(T_g)$ is the equilibrium value of ε_V.

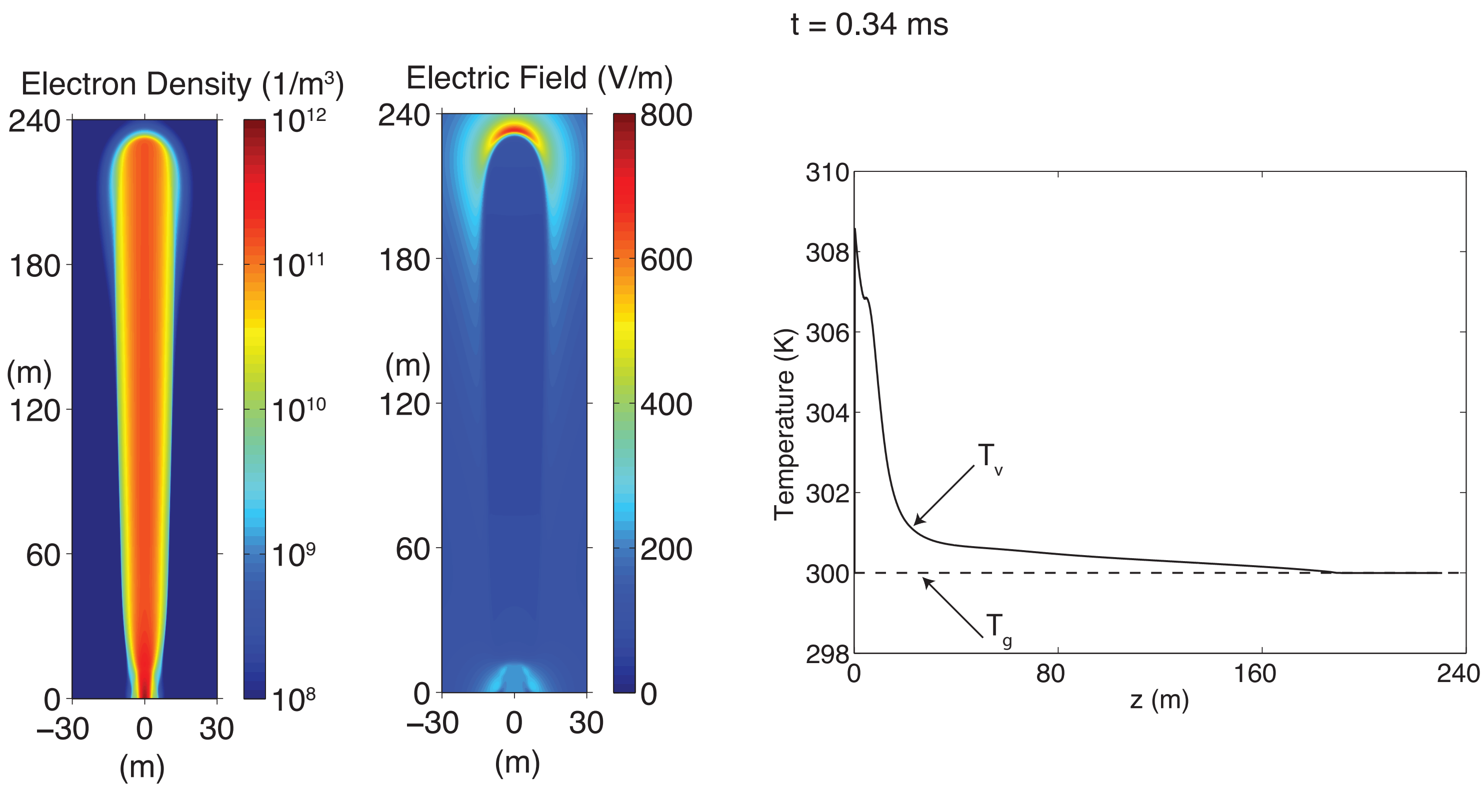
Rates and Coefficients for the Heating Model

- (a) Fractions of input energy transferred into vibrational excitation and 'fast heating' as a function of reduced electric field [*Hagelaar and Pitchford*, 2005]; (b) The vibrational-translational relaxation time at 70 km altitude [*Mnatsakanyan and Naidis*, 1986].



Heating Effects of a Sprite Streamer

- Heating effects of a positive streamer in an ambient field $E_0 = 15 \times N_{70}/N_0$ kV/cm, where N_{70} and N_0 are air densities at 70 km and 0 km altitude, respectively.



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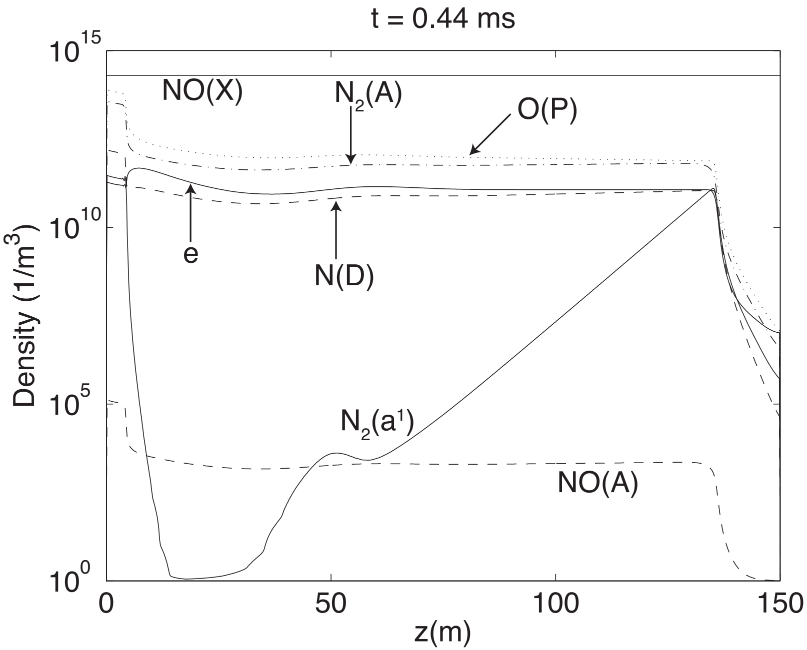
NO Chemistry for Sprite Streamers

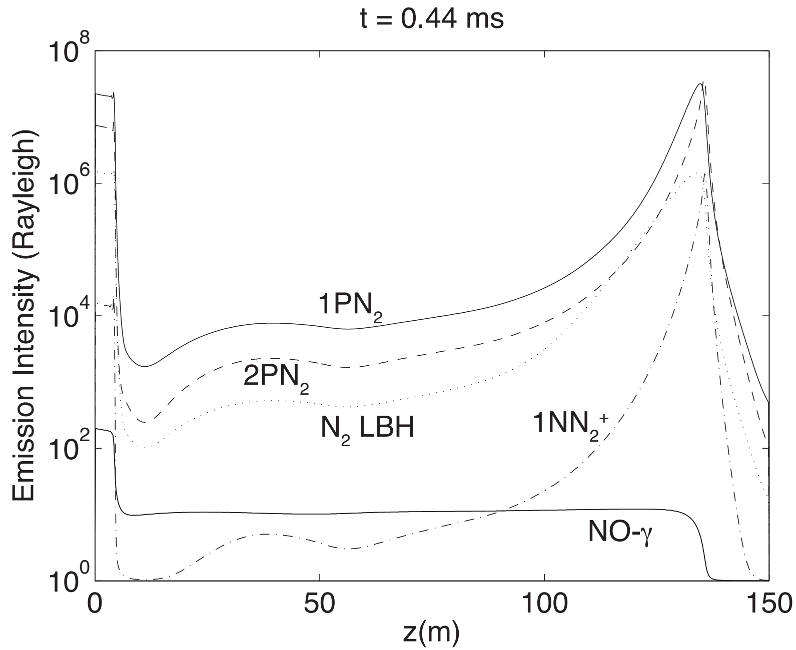
- Important species involved in NO chemistry: N_2, O_2, $N(^2D)$, $O(^3P)$, $N_2(A^3\Sigma_u^+)$, $NO(X^2\Pi_r)$, and $NO(A^2\Sigma^+)$

Reaction process or index	Reaction	Rate Coefficient [$f(E/N)$ denotes function of reduced electric field]
Electron collision reactions		
1	$e + N_2 \rightarrow e + N(^4S) + N(^2D)$	$f(E/N)$
2	$e + O_2 \rightarrow e + O(^3P) + O(^3P)$	$f(E/N)$
3	$e + N_2 \rightarrow e + N_2(A^3\Sigma_u^+)$	$f(E/N)$
4	$e + N_2 \rightarrow e + N_2(B^3\Pi_g)$	$f(E/N)$
5	$e + N_2 \rightarrow e + N_2(C^3\Pi_u)$	$f(E/N)$
6	$e + NO(X^2\Pi_r) \rightarrow e + NO(A^2\Sigma^+)$	$f(E/N)$
Chemical reactions		
7	$N(^2D) + O_2 \rightarrow NO(X^2\Pi_r) + O(^3P)$	5.20×10^{-18} m^3s^{-1}
8	$N_2(A^3\Sigma_u^+) + O(^3P) \rightarrow NO(X^2\Pi_r) + N(^2D)$	7×10^{-18} m^3s^{-1}
9	$N(^2D) + NO \rightarrow N_2 + O(^3P)$	6.0×10^{-17} m^3s^{-1}
Excitation		
10	$N_2(A^3\Sigma_u^+) + NO(X^2\Pi_r) \rightarrow N_2(X^1\Sigma_g^+) + NO(A^2\Sigma^+)$	8.75×10^{-17} m^3s^{-1}
Quenching		
11	$N(^2D) + N_2 \rightarrow N(^4S) + N_2$	1.70×10^{-20} m^3s^{-1}
12	$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2 + O_2$	8.75×10^{-19} m^3s^{-1}
13	$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2 + 2O(^3P)$	1.63×10^{-18} m^3s^{-1}
14	$NO(A^2\Sigma^+) + O_2 \rightarrow NO(X^2\Pi_r) + O_2$	1.62×10^{-16} m^3s^{-1}
Radiative transition		
15	$N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+) + h\nu$	1.7×10^5 s^{-1}
16	$N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g) + h\nu$	$2.0 \times 10^7 s^{-1}$
17	$NO(A^2\Sigma^+) \rightarrow NO(X^2\Pi_r) + h\nu$	5×10^6 s^{-1}

Modeling Results of a Positive Streamer at 70 km Altitude

- $E_0 = 5 \times \mathrm{N}_{70}/\mathrm{N}_0$ kV/cm, where N_{70} and N_0 are air densities at 70 km and 0 km altitude, respectively. The initial density of NO is set to be 2×10^{14} 1/m^3 [*Atreya*, Adv. Space Res., 1, 127, 1981].





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The principal results and contributions of this study can be summarized as follows:

- The three intensity ratios ($2PN_2$ to $1PN_2$, LBH N_2, and $1NN_2^+$) obtained from streamer modeling results generally agree with the ISUAL spectrophotometric measurements. These ratios depend on the magnitude of the ambient field and the polarities of streamers.

- At the initial stage, the $2PN_2/1NN_2^+$ ratio from ISUAL measurements is smaller than the ratio obtained from the streamer modeling. This implies that the maximum electric field driving the emissions of the sprite must be greater than $\sim 3E_k$, which is consistent with the conclusion drawn in [*Kuo et al.*, 2005; *Liu et al.*, 2006].

- Modeling results on a streamer developing for a period of 0.34 ms indicate that the perturbation of gas temperature is minimal and the vibrational temperature of N_2 molecules increases by several degrees K. However, the air heating by a streamer on longer time scales may be substantially accelerated due to kinetic effects [*Pasko and Bourdon*, 2007].

- Chemically active species, including $N_2(A)$, O and N, are effectively produced in the streamer discharges at the sprite altitudes.

- The $NO(A^2\Sigma^+)$ species in sprite streamers at 70 km altitude are mostly produced by interaction of $N_2(A^3\Sigma_u^+)$ species with high density ($\sim 2 \times 10^{14}$ 1/m^3) ambient $NO(X^2\Pi_r)$ molecules, leading to afterglow NO-γ emissions comparable to LBH N_2 emissions.

Publications and Conference Presentations to Date

- Refereed Journal Papers:
  - Liu, N. Y., S. Celestin, A. Bourdon, V. P. Pasko, P. Segur, and E. Marode, Photoionization and optical emission effects of positive streamers in air at ground pressure, *IEEE Trans. Plasma Sci.*, in press, 2008.
  - Liu, N. Y., S. Celestin, A. Bourdon, V. P. Pasko, P. Segur, and E. Marode, Application of photoionization models based on radiative transfer and the Helmholtz equations to studies of streamers in weak electric fields, *Appl. Phys. Lett.*, 91, 211501, 10.1063/1.2816906, 2007.
  - Liu, N. Y., and V. P. Pasko, Modeling studies of NO-γ emissions of sprites, *Geophys. Res. Lett.*, 34, L16103, 10.1029/2007GL030352, 2007.
  - Bourdon, A., V. P. Pasko, N. Y. Liu, S. Celestin, P. Segur, and E. Marode, Efficient models for photoionization produced by non-thermal gas discharges in air based on radiative transfer and Helmholtz equations, *Plasma Sources Sci. Technol.*, 16, 656-678, 10.1088/0963-0252/16/3/026, 2007.
- Conference Presentations:
  - Celestin, S., N. Y. Liu, A. Bourdon, V. P. Pasko, P. Segur, and E. Marode, Study of the efficient photoionization model 3-group SP3 for the modeling of streamer propagation, 35th EPS Plasma Physics Conference, Crete, Greece, June 9-13, 2008.
  - Liu, N. Y., and V. P. Pasko, Formation and propagation of negative streamers in sprites, 2008 URSI National Radio Science Meeting, Boulder, CO, January 3-6, 2008.
  - Liu, N. Y., V. P. Pasko, S. Celestin, A. Bourdon, P. Segur, and E. Marode, Photoionization models based on radiative transfer and Helmholtz equations for sprite streamer modeling, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract AE42A-06, 2007.

- (**Invited**) Liu, N. Y., S. Celestin, A. Bourdon, V. P. Pasko, P. Segur, and E. Marode, Application of photoionization models based on radiative transfer and Helmholtz equations to simulations of streamers in weak electric fields, Workshop on Streamers, sprites, leaders, lightning: from micro- to macroscales, Lorentz Center, Leiden University, Leiden, The Netherlands, October 8-12, 2007.
- (**Invited**) Pasko, V. P., and N. Y. Liu, Streamer theory of sprites, Workshop on Streamers, sprites, leaders, lightning: from micro- to macroscales, Lorentz Center, Leiden University, Leiden, The Netherlands, October 8-12, 2007.
- (**Invited**) Liu, N. Y., and V. P. Pasko, Modeling studies of NO-gamma emissions of sprites, 2007 North American URSI Meeting, Ottawa, ON, Canada, July 22-26, 2007.
- Pasko, V. P., N. Y. Liu, E. A. Kendall, R. A. Marshall, H. Edens, and P. R. Krehbiel, Observations of sprites from Langmuir Laboratory New Mexico on 12 September 2006, 2007 North American URSI Meeting, Ottawa, ON, Canada, July 22-26, 2007.
- Bourdon, A., V. P. Pasko, N. Y. Liu, S. Celestin, P. Segur, and E. Marode, Comparison of the classical integral model with Eddington approximation by non-thermal gas discharges in air, 28th International Conference on Phenomena in Ionized Gases, Prague, Czech Republic, July 15-20, 2007.
- Liu, N. Y., and V. P. Pasko, NO Chemistry and NO-gamma Emissions Associated with Sprite Streamers, 2007 CEDAR workshop, *Poster Sessions Booklet*, p. 20, Santa Fe, NM, June 24–29, 2007.
- Bourdon, A., V. P. Pasko, N. Y. Liu, S. Celestin, P. Segur, and E. Marode, Comparison of the classical integral model with Eddington approximation and Helmholtz equation based models for photoionization produced by non-thermal gas discharges in air, 2007 Aerospace Thematic Workshop: Fundamentals of Aerodynamic-Flow and Combustion Control by Plasmas, Varenna, Italy, May 28-31, 2007.
- (**Invited**) Liu, N. Y., and V. P. Pasko, The possibility of generation of NO-gamma emissions in sprite discharges, *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract AE41A-06, 2006.